Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-26, 2012

Study on Methodology for Establishment of the Minimum Allowable Fuel Channel Flow Rate in Steady State for CANDU Reactors Considering the Aging Effect

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1. Introduction

To assure safety of NPPs, cooling capacity must be greater than heat generation from reactor core. In particular, regional overpower should be prevented to guarantee cladding intactness and protect the public and environment from eventual radiation hazards. At this point, minimum allowable channel flow rate must be set and complied with.

In CANDU reactors, the maximum channel flow rate was set to 30 kg/s for single phase flow and 24 kg/s for two phase flow experimentally to prevent excessive vibration and maintain mechanical stability [1]. However, the minimum channel flow rate is not clearly set for CANDU reactors.

Considering characteristics of CANDU reactor, regional overpower can be deepened by creep in the pressure tube, change in the reactor inlet and outlet header temperatures and the transition of pressure difference between RIH and ROH caused by degradation. Thus, the methodology to evaluate minimum allowable channel flow rate considering the thermal-hydraulic aging factor is developed in this study.

2. Method and prerequisite for establishing minimum allowable channel flow rate

2.1 Computational code methodology

The procedure of the methodology is listed in Table 1, and the computational code system used in this study is depicted in Figure 1.

Table 1. Procedure of methodology

Step 1.	Selection of code, standard noding, plant & Identification of safety/operational limits
	- Selection of computational code, standard noding and plant
	- Checking applicability of code, noding
	- Identification of safety and operating limit
Step 2.	Establishment of minimum allowable fuel channel flow rate without aging effect
	- Sensitivity analyses on initial fuel channel mass flow rate
	- Comparison between sensitivity results and limiting values
	- Setting minimum allowable fuel channel flow rate without aging effect
Step 3.	Establishment of minimum allowable fuel channel flow rate considering one aging element
	- Selection of operating time & aging elements
	- Calculating $\lambda(t)$ of aging elements using degradation model
	- Steady state analyses
	- Checking change of HTS parameters and selection of critical parameter
	- Setting minimum allowable fuel channel flow rate considering one aging element using bias of critical parameter
Step 4.	Establishment of minimum allowable fuel channel flow rate considering compound element
	- Selection of operating time
	- Calculating $\lambda(t)$ of aging elements using degradation model
	- Determination of most conservative aging element combination
	- Acquisition of 124 LHS set within 2σ
	- Steady state analyses on 124 set
	- Seeking 3rd maximum value and cheking change of HTS parameters
	- Setting minimum allowable fuel channel flow rate considering one aging element using bias of 3rd maximum parameter

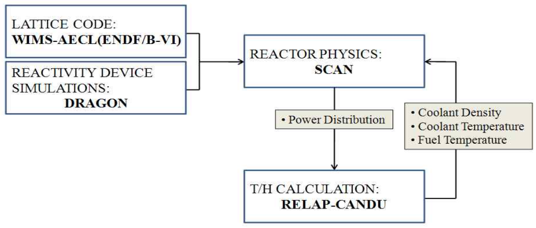

Fig. 1. Computational code system

2.2 Limiting condition and allowable criteria

The safety limits, operating limits, and allowable criteria listed below are used to evaluate the validity of the flow rate [1,2].

Safety Limits
- Maximum channel power < 9.03 MW (Mode 1, 2)
- OHD pressure < 11.77MP(g) (Mode 1, 2, 3)

Operating Limits
- Channel power from reactor to coolant: < 7.07MW
- Bundle power from reactor to coolant: < 898kW
- Pressurizer level: 0.8m < level < 13.91m
- OHD quality: < 4% etc.

Allowable Criteria
- Stored energy of hottest fuel rod: 840kJ/kg-UO_2
- Cladding temperature: < 800℃ - intact cladding
- Pressure tube temperature: < 600 ℃
- Maximum channel power: <7300kW
- Maximum bundle power: <935kW etc.

2.3 Degradation elements

The aging elements clarified in the previous studies are used to evaluate the degradation effect [3]. The aging elements are listed in Table 2.

Table 2. Aging elements related to the operating parameter.

Component	Ageing Element
Fuel Channel	Roughness, Loss Coefficient, Hydraulic Diameter, Flow Area
Pump	Pump Head, Pump Rated Flow
Steam Generator	Roughness, Hydraulic Diameter, S/G Divider Plates Leakage Area
Inlet Feeder + End Fitting	Roughness

3. Establishment of the minimum allowable fuel channel flow rate

3.1 Minimum allowable channel flow rate without aging

To determine the minimum allowable fuel channel flow rate, a sensitivity analysis was fulfilled by varying flow rate from 90% to 115% of the nominal value (1900 kg/s). As a result, it is identified that many limits and criteria are satisfied except for the OHD quality. Thus the optimal flow rate value meeting the criteria of the OHD quality was evaluated using the cubic fit of path 4, which is the most limiting path and the value of which is **1938.6kg/s** per 95 channels. (See Figure 2)

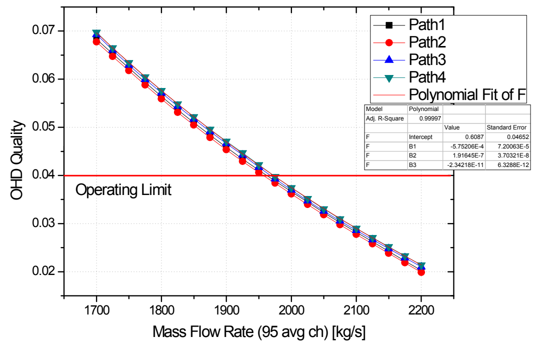

Fig. 2. Minimum flow rate without aging effect

3.2 Minimum allowable channel flow rate considering a single aging element

The aging rates for 9 aging elements at 10 year were determined according to the model developed by Y.W. Choi et al. [3]. Using this aging rate, steady state analyses were conducted. From these analyses, it was identified that OHD quality is the limiting criteria and the most affecting aging element is the fuel channel hydraulic diameter. Through these analyses, the bias of the OHD quality was determined as 0.0052. The derived minimum allowable fuel channel flow rate applying the bias is **2030.6 kg/s** per 95 channels. (See Figure 3)

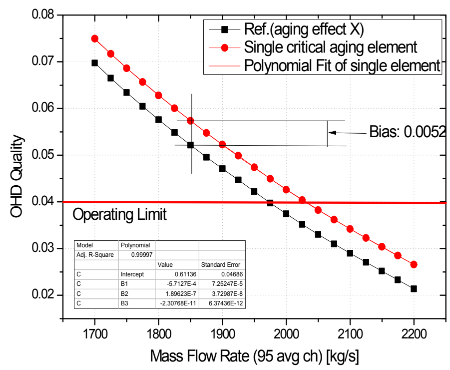

Fig. 3. Minimum flow rate considering single aging element

3.3 Minimum allowable channel flow rate considering compound aging effect

According to Y.W.Choi et al., the most conservative set of aging elements is a combination of hydraulic diameter, fuel channel flow rate, and pump rated flow rate [3]. Using Latin hypercube sampling and 3rd Wilk's formula, 124 random sets of aging rate values on conservative aging elements set is extracted, and steady state analyses are conducted on 124 cases. The bias of the OHD quality, which is the limiting criteria, is determined from the case at which the third maximum OHD quality, an upper 95% value with a 95% confidence level, is obtained. The value of the bias is 0.0327. Applying this bias, the minimum allowable fuel channel flow rate considering compound aging elements is determined as **2417.0 kg/s** per 95 channels (See Figure 4). However, this value exceeds the maximum channel flow rate for two phase flow. This exaggerated value might be caused by excessive conservatism in the degradation model.

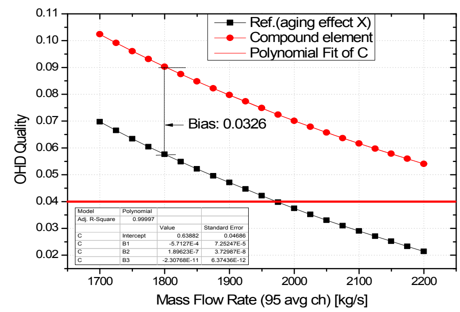

Fig 4. Minimum flow rate considering compound aging effect

4. Conclusions

CANDU reactors are generally operated with 110% of the nominal flow rate (2100kg/s) to secure the safety margin, although the design value of flow rate is set to 1900kg/s. However, the minimum allowable flow rate must be determined and complied to enhance reactor safety by assuring cooling capacity. In this study, the minimum allowable flow rate per 95 channels in steady state is determined as 1938.6 kg/s with no aging, 2030.6 kg/s for a single aging element, 2417.0 kg/s for conservative set of aging elements. To apply this minimum allowable fuel channel flow rate, however, modification of aging model is needed to eliminate excessive conservatism and realize minimum flow rate.

REFERENCES

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[2] C.K. Sung et al., "Establishment of CANDU Limiting Condition for Operation and Operational Mode" KEPCO, 2002
[3] Y.W.Choi et al., "A Statistically-engineered approach for assessing aging effects on thermal-hydraulic elements for CANDU reactors", Annals of Nuclear Energy, Vol 38, pp.1527-1544 (2011)